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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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EFFECT OF ADVANCE RATIO ON FLIGHT PERFORMANCE OF A MODIFIED SUPERSONIC PROPELLER

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SUMMARY

Results are presented of a flight investigation to determine the aerodynamic characteristics of a supersonic propeller modified by the incorporation of higher than optimum advance angles. The propeller was designed for a forward Mach number of 0.95, an advance ratio of 3.2, and a power coefficient of 0.42. The efficiency of the propeller is approximately 79 percent at a Mach number of 0.95. At lower Mach numbers the efficiency is higher, being about 85 percent at a Mach number of 0.75. The departure from optimum angle of advance has a small effect for the advance ratios investigated.

INTRODUCTION

The National Advisory Committee for Aeronautics is engaged in a program of flight research on propellers designed for transonic forward flight. The primary objective of the program is to assess the relative importance of design parameters. Parameters considered to be of importance are (1) optimum angle of advance and (2) minimum-thickness-ratio distribution.

In the transonic range near a Mach number of 1, profile efficiency is the primary consideration since profile losses are high whereas the induced losses are low. Consequently, the most efficient propeller is the one for which the profile efficiency is maximized. Maximum profile efficiency occurs at an angle of advance close to 45°. The high rotational speeds required to maintain this advance angle at transonic forward Mach numbers are such that the upper stress limits of available materials must be used. In addition to the high stresses, the high rotational speeds result in supersonic helical Mach numbers along the blade and produce high noise levels. These conditions have generated the designation "supersonic propeller" for propellers of this type.

The second parameter of importance in the design of propellers for transonic forward speeds is minimum thickness ratio. In order to achieve maximum profile efficiency, values of lift-drag ratio as high as possible

are required. At supersonic speeds high lift-drag ratios are achieved only by low thickness ratios. Thus, minimum values of thickness ratios are desired.

Both of these concepts (optimum angle of advance and minimum thickness ratio) were incorporated in the design of the supersonic propeller of reference 1. This propeller produced high aerodynamic efficiency, being on the order of 79 percent at the design Mach number of 0.95. The propeller discussed herein incorporated the same thickness-ratio distribution as the supersonic propeller but had greater than optimum pitch distribution and lower rotational speeds. The lower rotational speeds allowed lower propeller weights and lower noise levels. Consequently, because of lower values of Mach number along the blade but still mostly supersonic under design conditions, the term "modified supersonic" has been applied to this type of propeller. The modified supersonic propeller was designed for a forward Mach number of 0.95, an advance ratio of 3.2, and a power coefficient of 0.42; it has the same thickness ratio as the supersonic propeller of reference 1. The angle of advance is approximately 60° at the 0.7 radius station.

The purpose of this investigation was to compare the resulting aerodynamic performance of the modified supersonic propeller with that of the supersonic propeller (ref. 1) and thus obtain an assessment of the importance of one of the two design parameters aforementioned.

SYMBOLS

b	blade chord, ft
C_P	propeller power coefficient, $P/\rho n^3 D^5$
C_T	propeller thrust coefficient, $T/\rho n^2 D^4$
D	propeller diameter, ft
h	blade thickness, ft
J	propeller advance ratio, V/nD
L/D	lift-drag ratio
M	Mach number
n	propeller rotational speed, rps

p static pressure, lb/sq ft

p_t total pressure, lb/sq ft

P power, ft-lb/sec

r radius of an element on blade from center line of rotation, ft

r_s radial dimension from center line of rotation, ft

R propeller tip radius, ft

T thrust, lb

$x = 2r/D$

$x_s = 2r_s/D$

β blade angle, deg

Δp_t total-pressure rise in slipstream, lb/sq ft

η propeller efficiency

ρ density of air, slugs/ft^3

Subscripts:

l local conditions

∞ free-stream conditions

t propeller tip condition

APPARATUS AND TEST PROCEDURE

Test Vehicle

The propeller test vehicle is the McDonnell XF-88B propeller research airplane and is shown in figure 1. The airplane is capable of speeds in excess of a Mach number of 1.0. It is powered by two J-34 jet engines and one T-38 turboprop. The turboprop engine drives the test propeller at 1,710 revolutions per minute for the tests reported herein, although by interchanging gears it can provide propeller speeds of 3,600 or 6,000 revolutions per minute. The engine can deliver 2,500 brake horsepower at sea

level and is a forerunner of the T-56 presently installed in contemporary turboprop transports, both military and commercial. A view of the engine is shown in figure 2.

Test Propeller and Spinner

The modified supersonic propeller is shown mounted on the research airplane in figure 1. This propeller is a three-blade 9.8-foot-diameter configuration with the same geometric characteristics and plan form as the propeller of reference 1, the main difference being in the pitch distribution. The blade-form curves are shown in figure 3. The design conditions are an advance ratio of 3.2 at a forward Mach number of 0.95 at 40,000 feet. The blades are composed of 16-series symmetrical airfoil section with thickness ratio varying from 0.02 at the tip to 0.054 at the spinner juncture. The blades were fabricated from 4340 alloy steel and are of solid construction. This alloy has an ultimate tensile strength of 180,000 pounds per square inch.

The blades were tested in conjunction with a 41° conical spinner which was sealed at the base but open at the blade juncture. This spinner causes a reduction in the flow velocity through the plane of the propeller; therefore, the propeller does not sense the true free-stream conditions. Measurements were made to a point corresponding to 0.5 radius on this propeller on a replica nonrotating spinner to show this alteration in flow velocity. This alteration is shown in figure 4.

Instrumentation and Data Reduction

The XF-88B airplane is provided with a variety of instrumentation. The power is determined from a commercially available electronic shaft torquemeter which has been modified by the Langley laboratory. This instrument is considered to be accurate to ±20 horsepower or a ΔC_P of 0.006 at 30,000 feet.

Propeller thrust is measured by a slipstream survey rake in a manner described in reference 1. Total thrust is obtained from an integration of the total-pressure rise measured along the rake from the side of the fuselage to the rake station showing zero incremental pressure. The thrust distributions were computed from the measured total-pressure distributions by the use of the short-form equation

$$\frac{dC_T}{d\left(x_s^2\right)} = \frac{\pi}{4} \frac{\left(\frac{p_\infty}{p_{t,\infty}}\right)^{5/7} \Delta p_t}{\rho n^2 D^2}$$

derived in reference 1. Inasmuch as the total-pressure probes are insensitive to small changes in angle, the thrust calculated in this fashion does not account for rotation of the slipstream. A correction for slipstream rotation as a function of section power was made; the section power was determined by measurement of slipstream-stagnation-temperature rise as outlined in reference 1. This correction averages about 3 percent.

Standard NACA instrumentation was utilized for measuring airspeed, altitude, temperature, and accelerations. A schematic drawing showing the instrumentation is shown in figure 5.

RESULTS AND DISCUSSION

Propeller Efficiency

Figure 6 presents the variation of propeller efficiency with forward Mach number. Also plotted are the corresponding advance ratio, power coefficient, and thrust coefficient. The Mach number is the free-stream Mach number and does not include the alteration caused by the 41° conical spinner. This alteration causes a reduction in section Mach number at least in the inboard portion of the blade and must be reflected as an increase in section lift-drag ratio. Free-stream velocity is used in the determination of propeller efficiency as the thrust is measured by the integration of the slipstream survey at the rake station, which is out of the influence of the spinner.

As shown in figure 6, the efficiency is 79 percent at the design Mach number of 0.95. The design advance ratio was exceeded at the design Mach number because the tests were carried out at altitudes lower than design. This was necessary due to the limitations of the altitude capability of the XF-88B airplane.

The variation of efficiency with Mach number is replotted in figure 7 together with that of the supersonic propeller (ref. 1) to afford a direct comparison of performance. The curve for the variation of efficiency with Mach number has a more conventional appearance than that for the supersonic propeller of reference 1 because of the reduction in advance ratio. Also plotted in figure 7 is the operating advance ratio. As can be seen, the efficiency level is higher at the lower Mach numbers for the modified supersonic propeller and is about the same for the design Mach number. A comparison at a Mach number of 0.75 shows that the modified supersonic propeller has an efficiency of 85 percent, 5 percent higher than the supersonic propeller.

This comparison indicates that for this departure from the optimum advance ratio there was little effect at design conditions. The reason for the small effect can be seen in the variation of lift-drag ratios of low-thickness-ratio airfoils. This is an important consideration, because with the modified propeller more reasonable rotational speeds result with much less noise and lower propeller weight. The noise characteristics of this propeller have been reported on in reference 2.

Thrust Distributions

Thrust distributions for the range of Mach numbers from $M_\infty = 0.750$ to $M_\infty = 0.948$ are shown in figure 8 and are presented as variations in differential thrust coefficient with radial stations for both left and right survey rakes.

The thrust distributions are smooth and uniform with no breakdowns in the outboard regions such as occur with subsonic propellers encountering compressibility losses. The smooth distribution is a result of the use of thin symmetrical blade sections which have very little change in lift-curve slope and angle of zero lift through the transonic region. It is to be noted that the differential thrust extends past the propeller tip station $\left(x_s^2 = 1.0\right)$; this extension is due to the expansion of the air mass by the conical fuselage and spinner.

The characteristic difference in thrust-distribution levels between right and left survey rakes resulting from propeller-thrust-axis inclination is shown in figure 8. The decrease in difference between right and left thrust distributions as the Mach number increases reflects the usual decrease in angle of inclination of the thrust axis with forward speed. The difference continues to decrease until at $M_\infty = 0.926$ the two surveys are coincident; this agreement indicates an angle of inclination of the thrust axis of approximately 0°. Further increase in Mach number to 0.948 results in an increase in angle of inclination. This result is in agreement with the variation in the slope of the lift curve and zero lift angle of the airplane beyond the force-break Mach number.

Comparison With Theoretical Calculations

Calculation of the optimum efficiency of this propeller at the design forward Mach number of 0.948 in an undisturbed free stream yields a value of 81 percent which is indicated by the solid square in figure 6. These calculations assume section lift coefficients for maximum L/D. Inasmuch as the propeller was designed to operate in this fashion, the power coefficient calculated from the resulting power loading obtained in these calculations is considered the design power coefficient and has the value of 0.42. As can be seen in figure 6, the experimental value of the power

coefficient is fairly close to the design or optimum power coefficient. Hence, the experimental value of propeller efficiency is very close to the optimum. On the basis of the data of figure 4 and the assumption of a 10-percent reduction in the flow velocity through the propeller, the calculated propeller efficiency is 84 percent because of the higher available L/D ratios.

CONCLUDING REMARKS

Results are presented of a flight investigation to determine the aerodynamic characteristics of a modified supersonic propeller at forward Mach numbers up to about 0.95. The propeller was designed for a forward Mach number of 0.95, an advance ratio of 3.2, and a power coefficient of 0.42.

The efficiency of the propeller is approximately 79 percent at a Mach number of 0.948 and an advance ratio of 3.5. At lower Mach numbers the efficiency is higher, being about 85 percent at a Mach number of 0.75. The supersonic propeller produces the same efficiency at a Mach number of 0.95 but is 5 percent lower than that of the modified supersonic propeller at a Mach number of 0.75. The departure from optimum angle of advance has a small effect for the advance ratio investigated.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., June 27, 1958.

REFERENCES

1. Hammack, Jerome B., Kurbjun, Max C., and O'Bryan, Thomas C.: Flight Investigation of a Supersonic Propeller on a Propeller Research Vehicle at Mach Numbers to 1.01. NACA RM L57E20, 1957.

2. Kurbjun, Max C.: Noise Survey Under Static Conditions of a Turbine-Driven Full-Scale Modified Supersonic Propeller With an Advance Ratio of 3.2. NACA TN 4172, 1957.

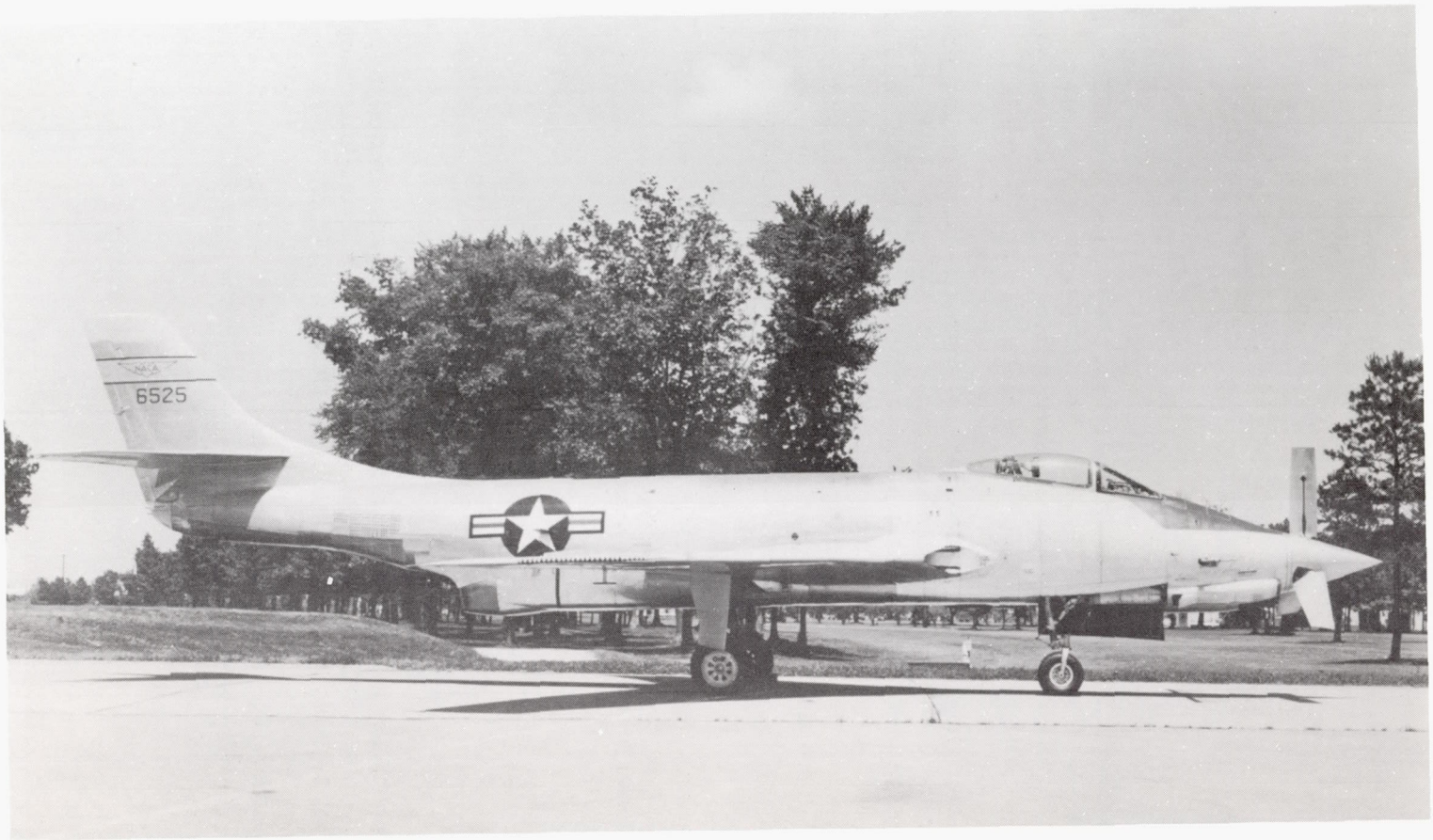

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Figure 1.- Photograph of McDonnell XF-88B airplane showing test propeller installation.

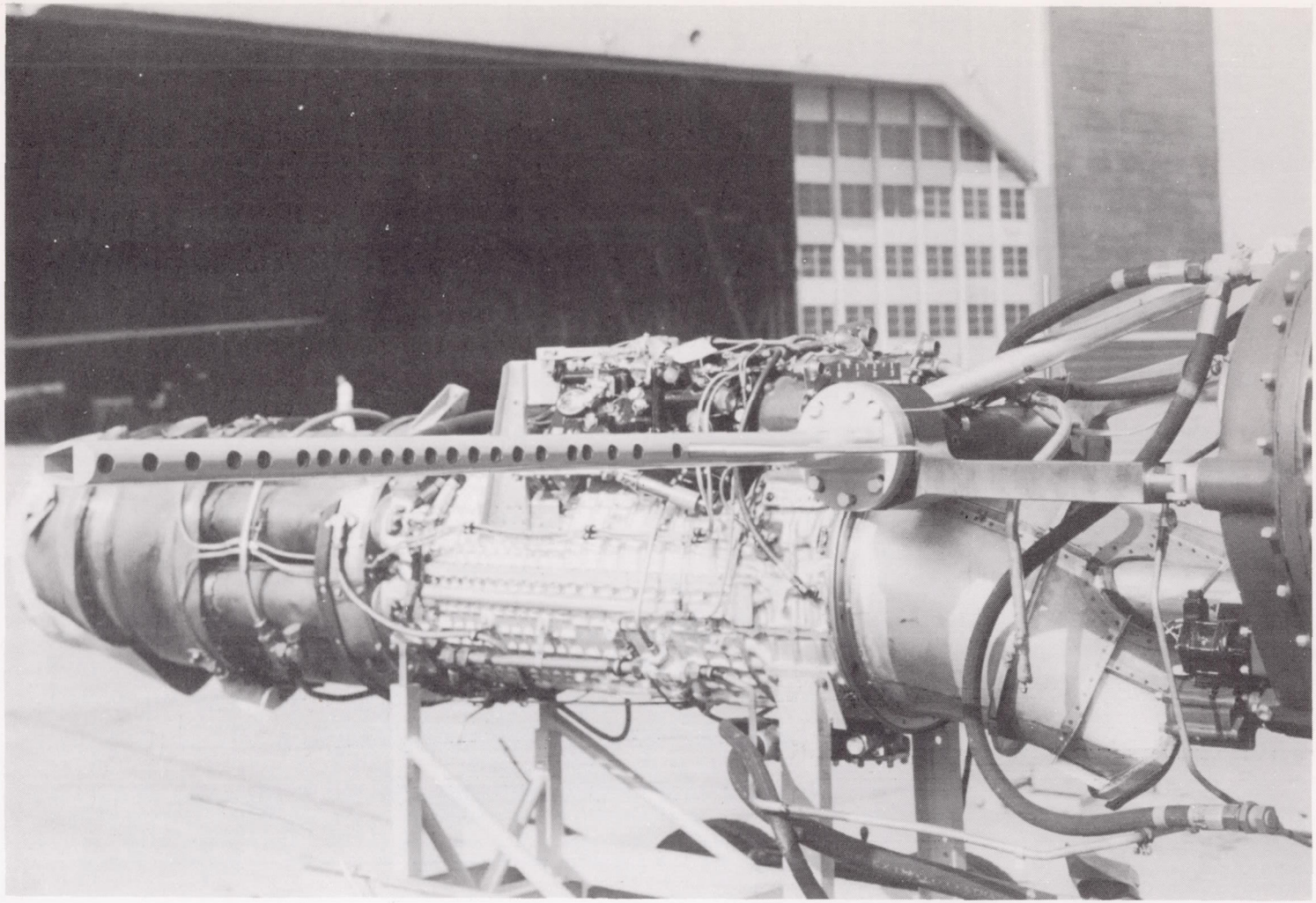

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Figure 2.- The T-38 turboprop engine showing the power section and special gearbox.

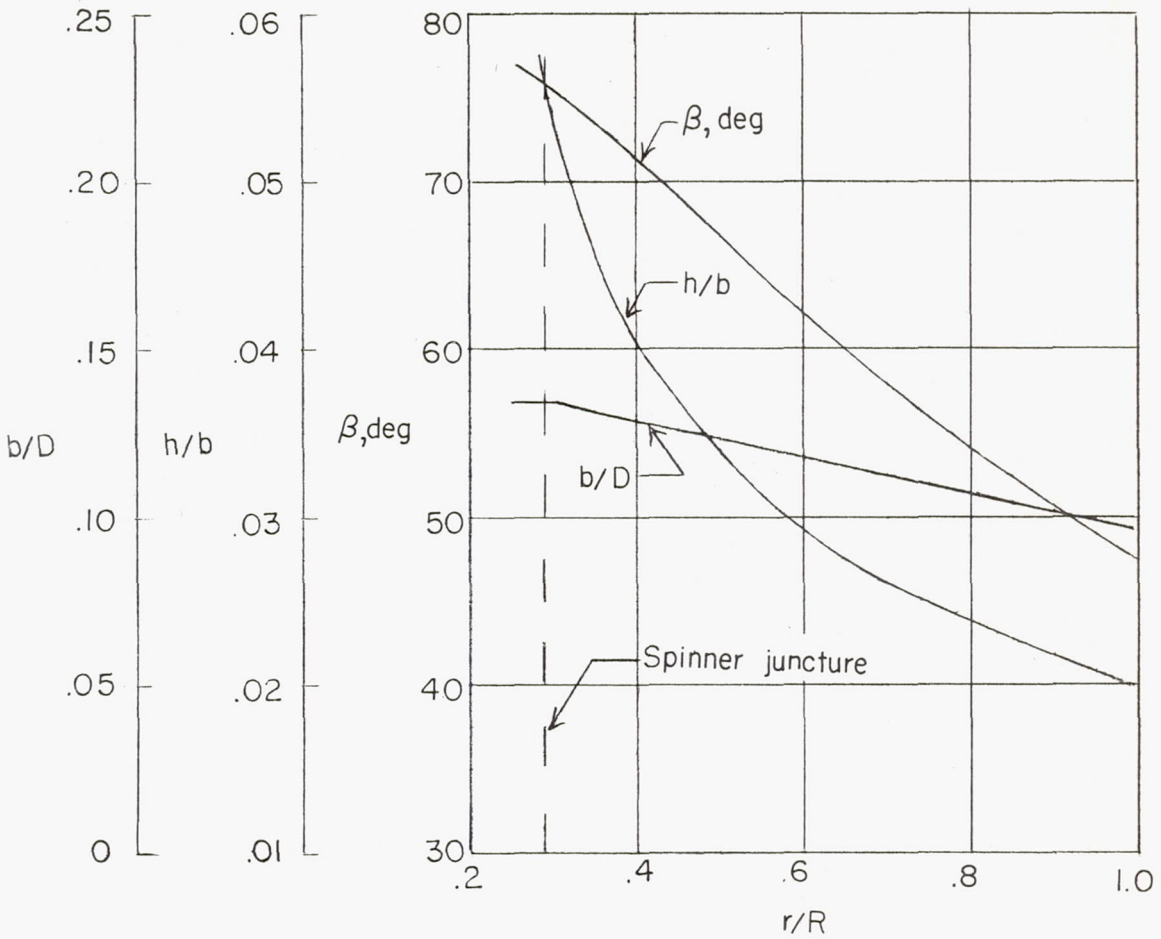


Figure 3.- Blade-form curves of modified supersonic propeller used in present investigation.

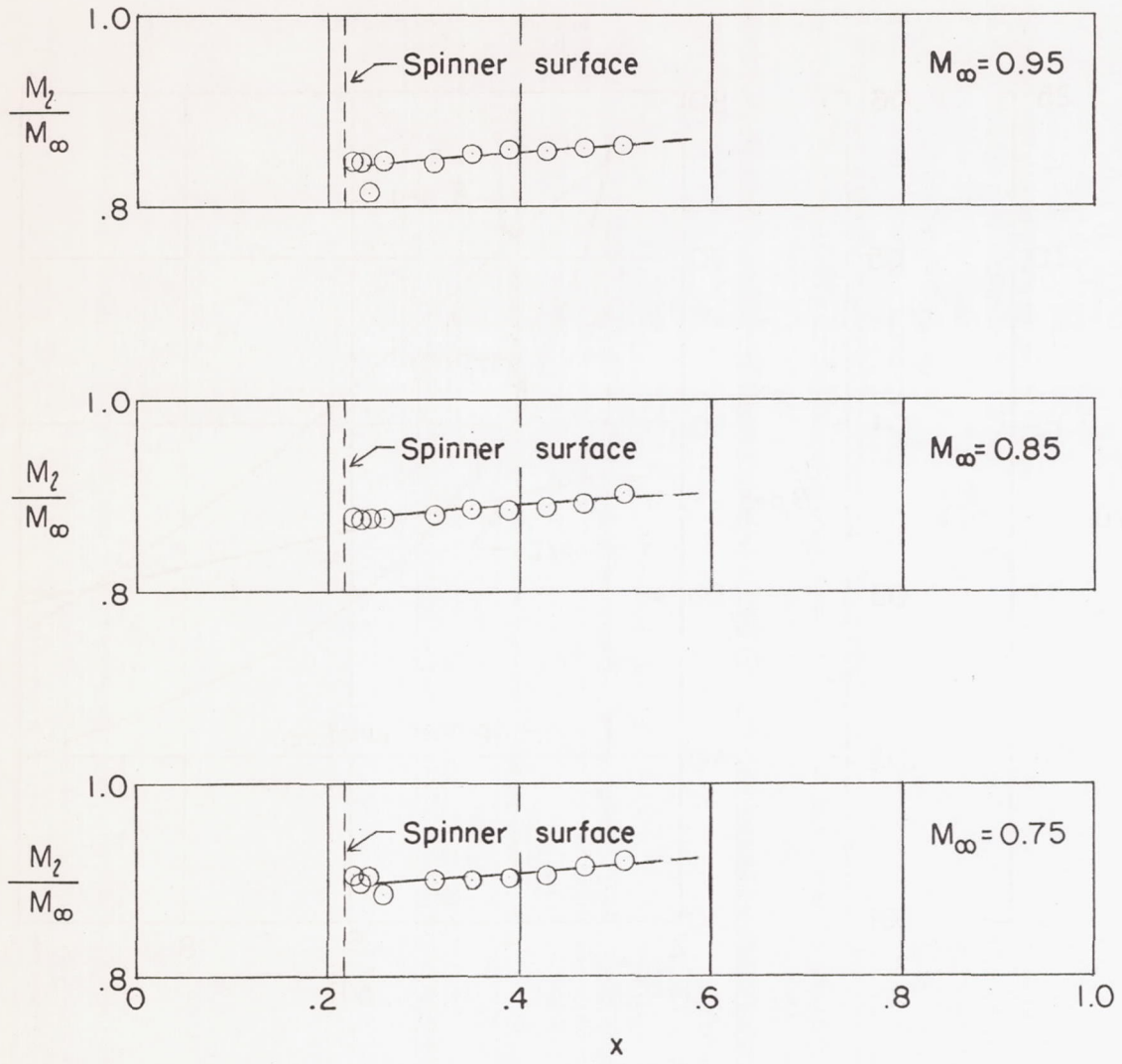


Figure 4.- Variation of local Mach number with radial distance.

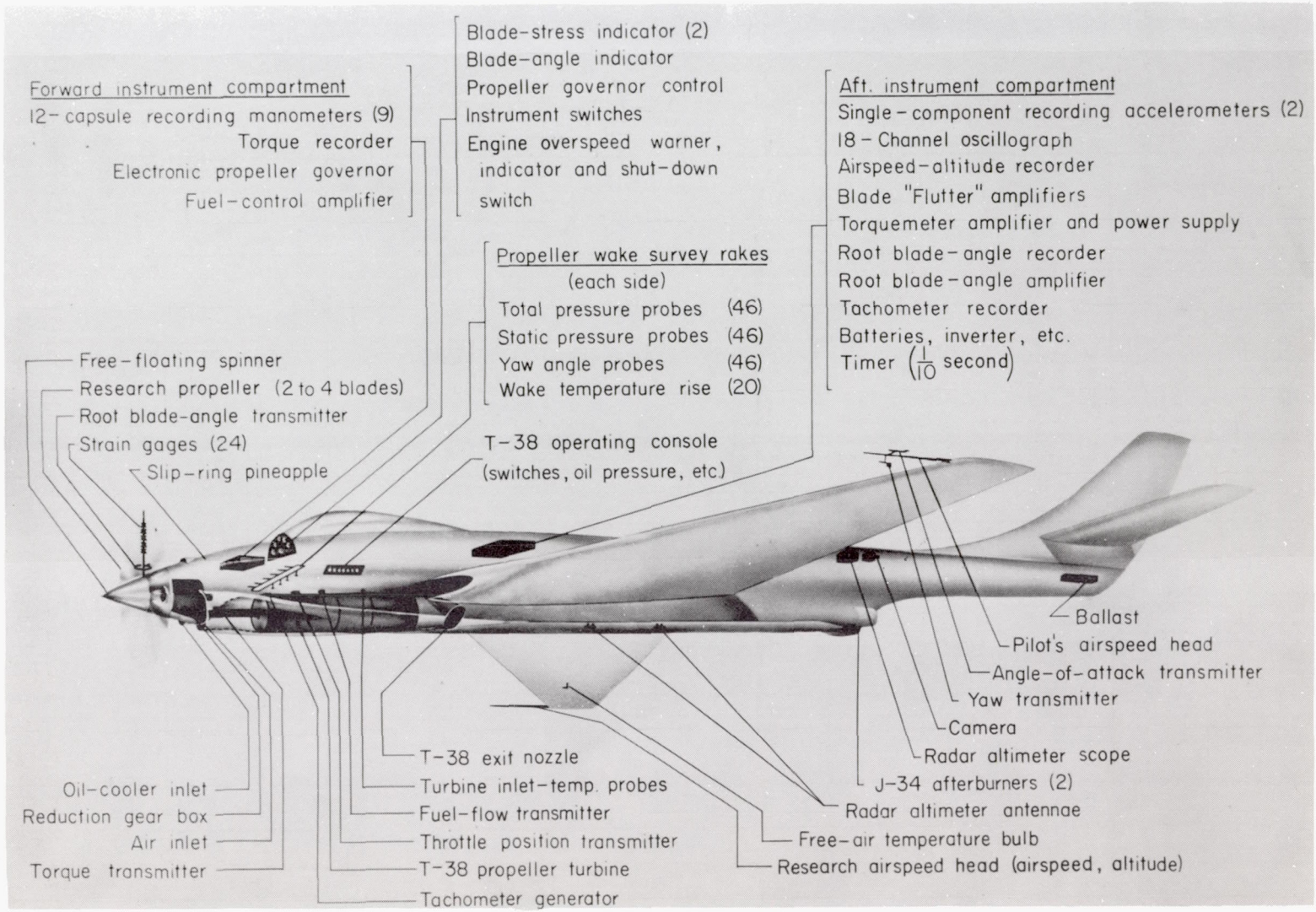


Figure 5.- Instrumentation layout on the McDonnell XF-88B airplane. L-57-1077

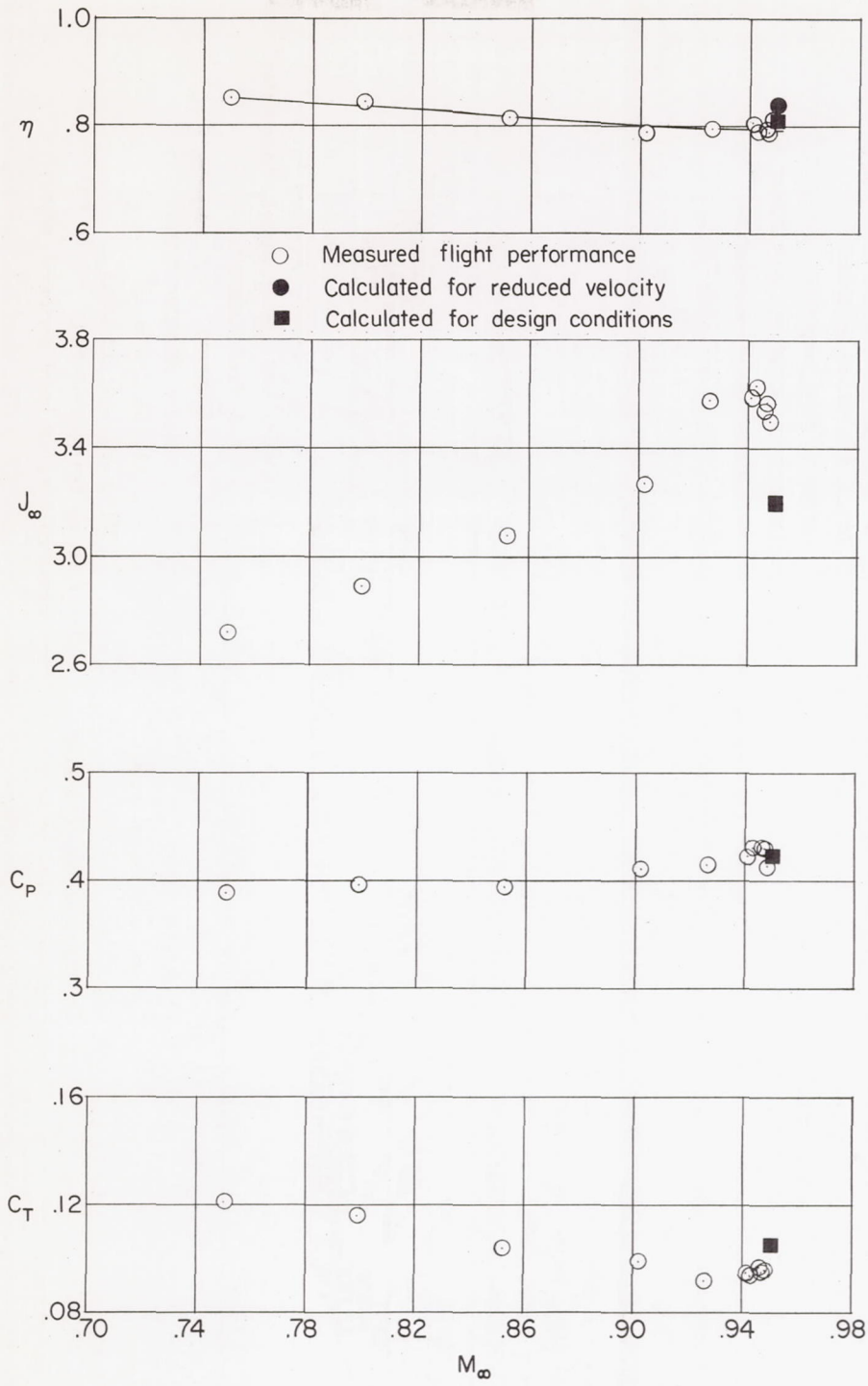


Figure 6.- Performance characteristics of the modified supersonic propeller for flight Mach numbers up to 0.95.

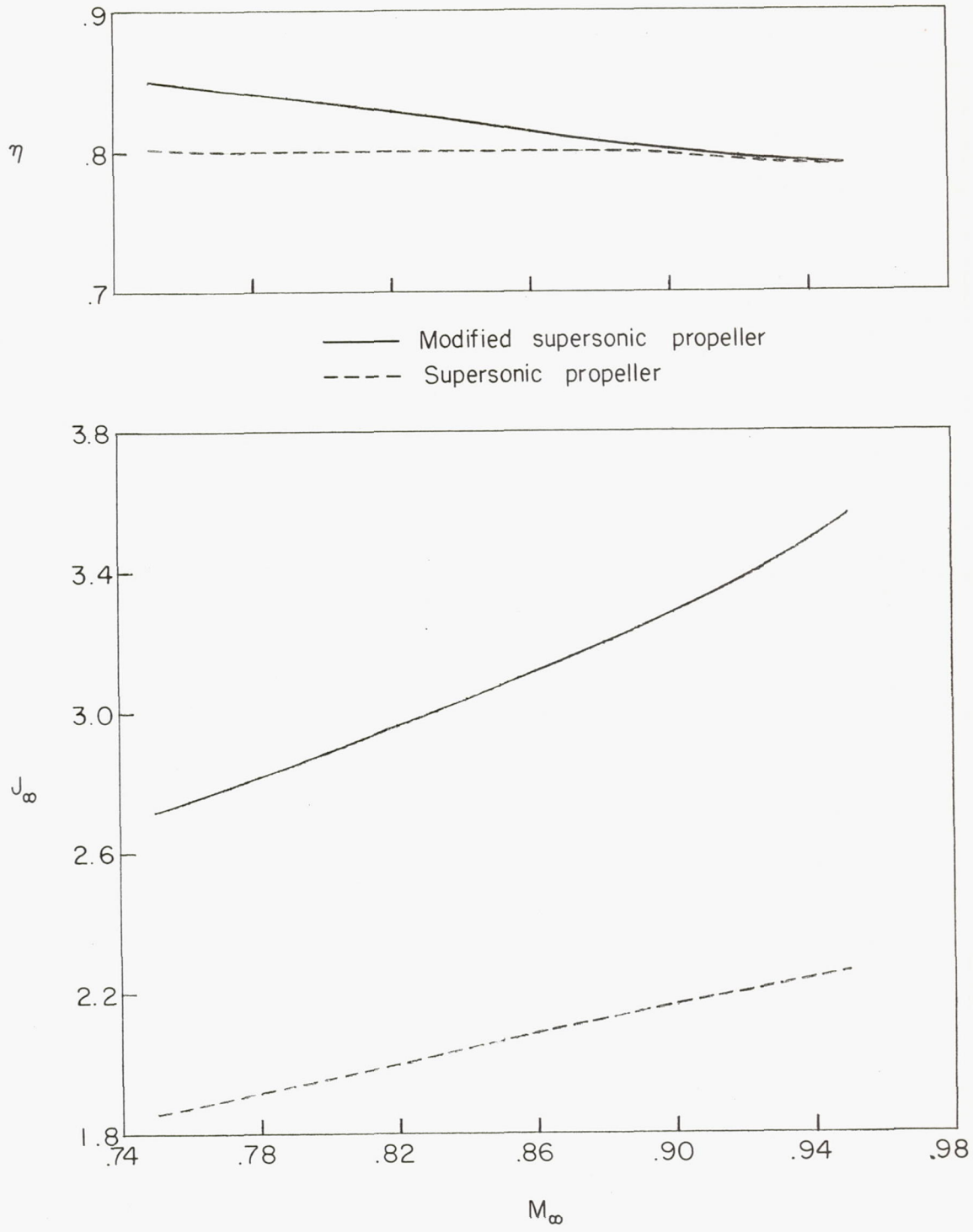
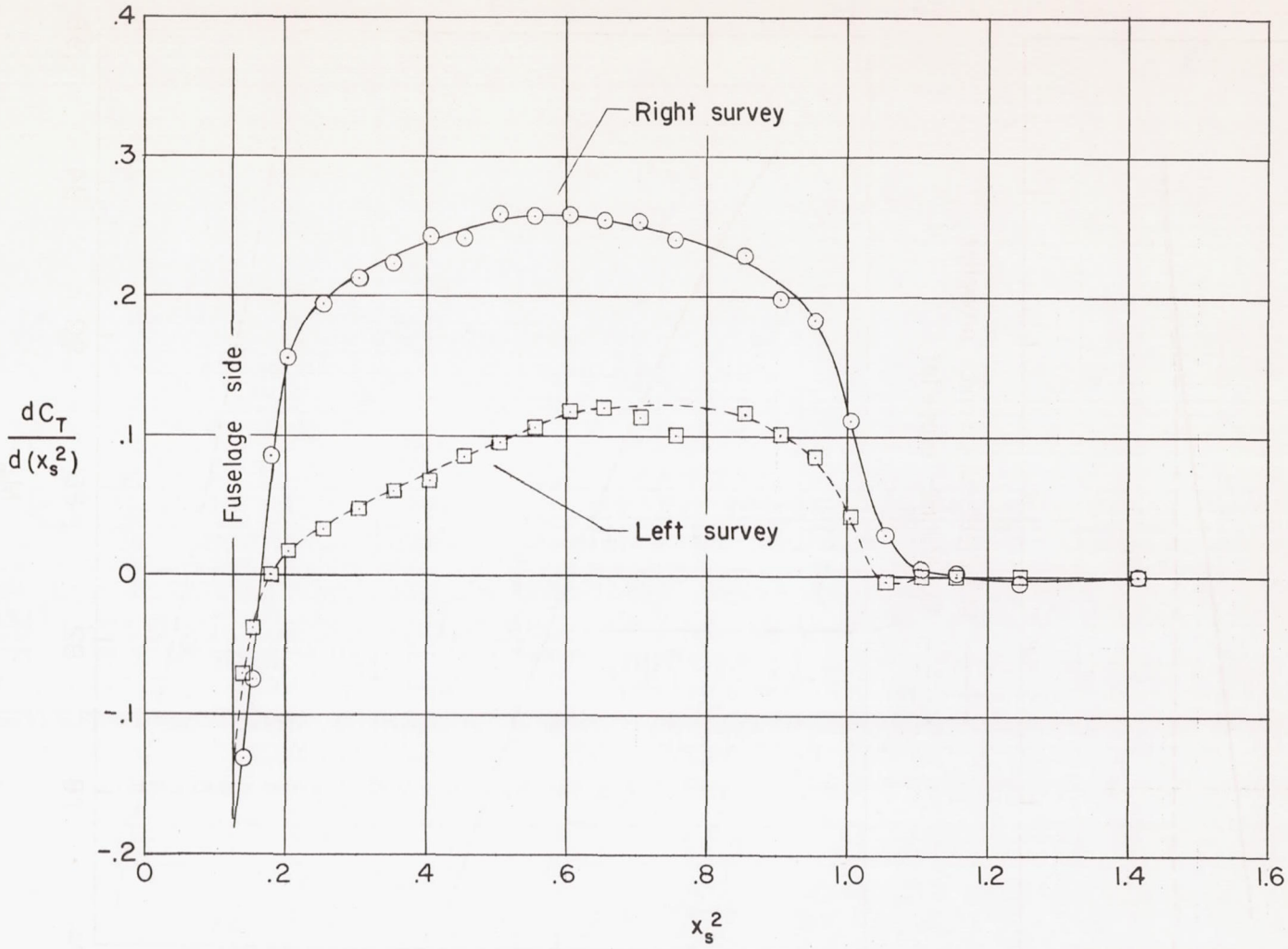
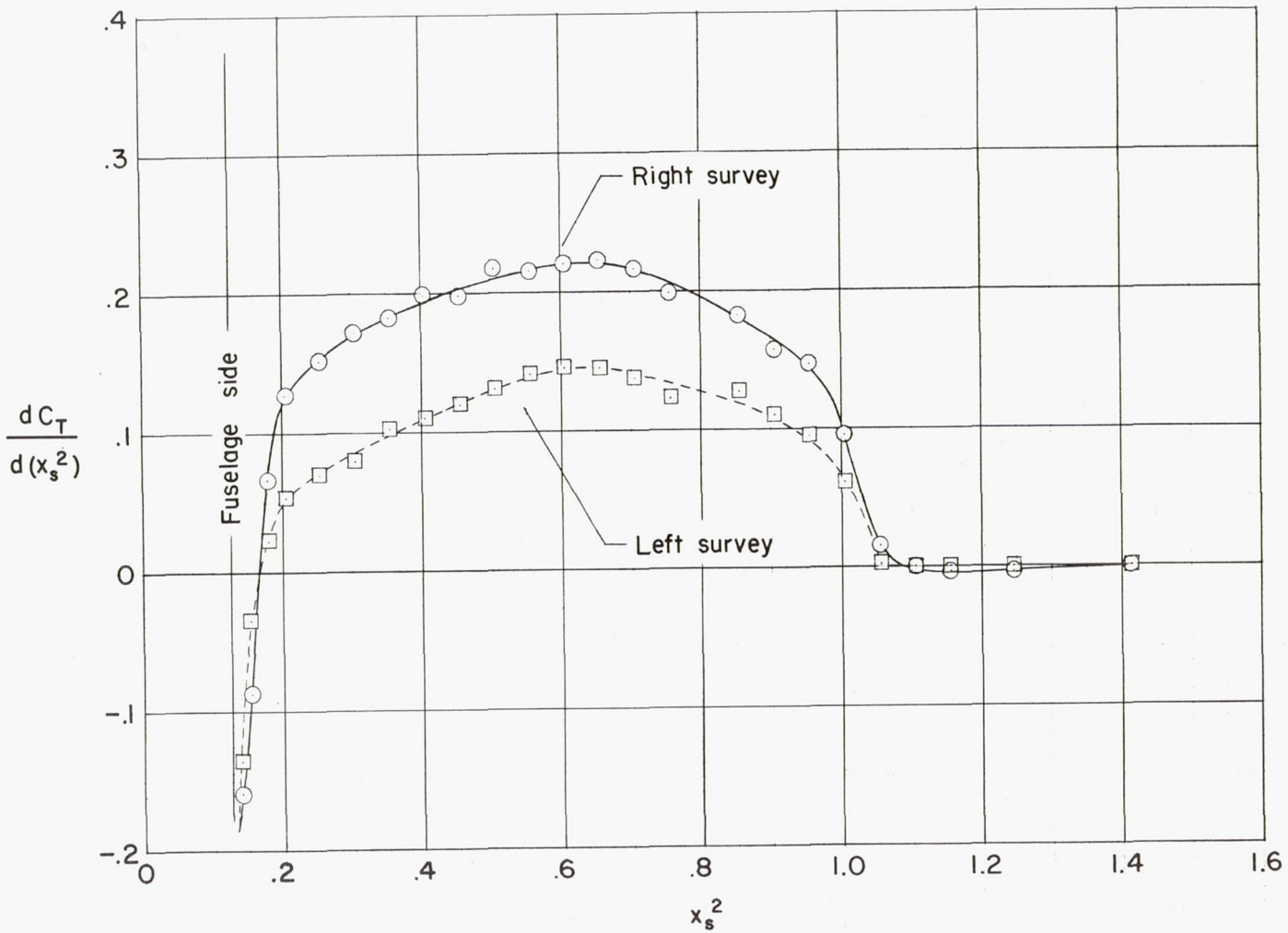


Figure 7.- Variation of efficiency and advance ratio with free-stream Mach number for modified supersonic and supersonic propellers.



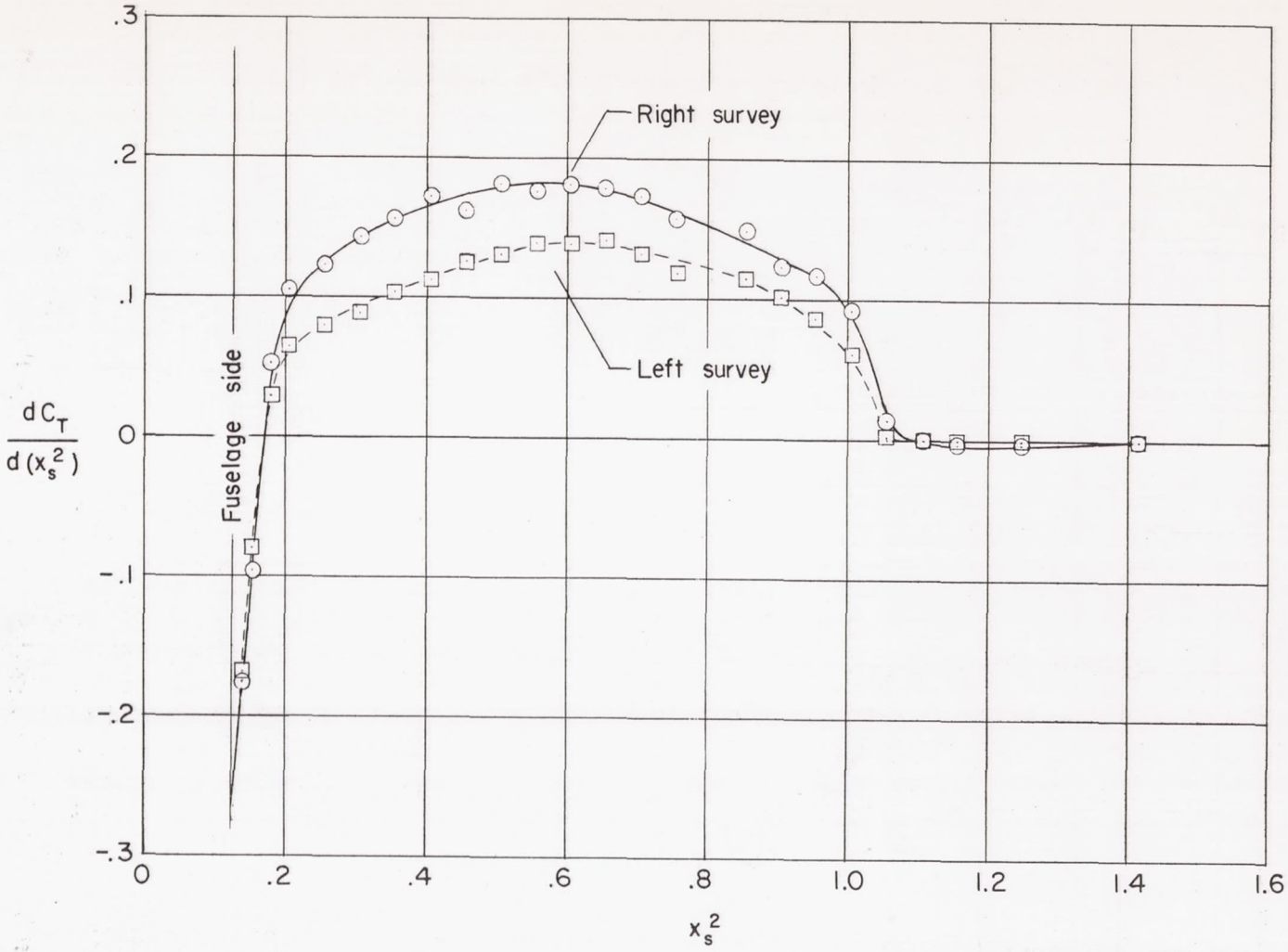
(a) $M_\infty = 0.750$; $J_\infty = 2.72$; $C_P = 0.388$; $M_t = 1.146$.

Figure 8.- Thrust distributions determined from survey rake.



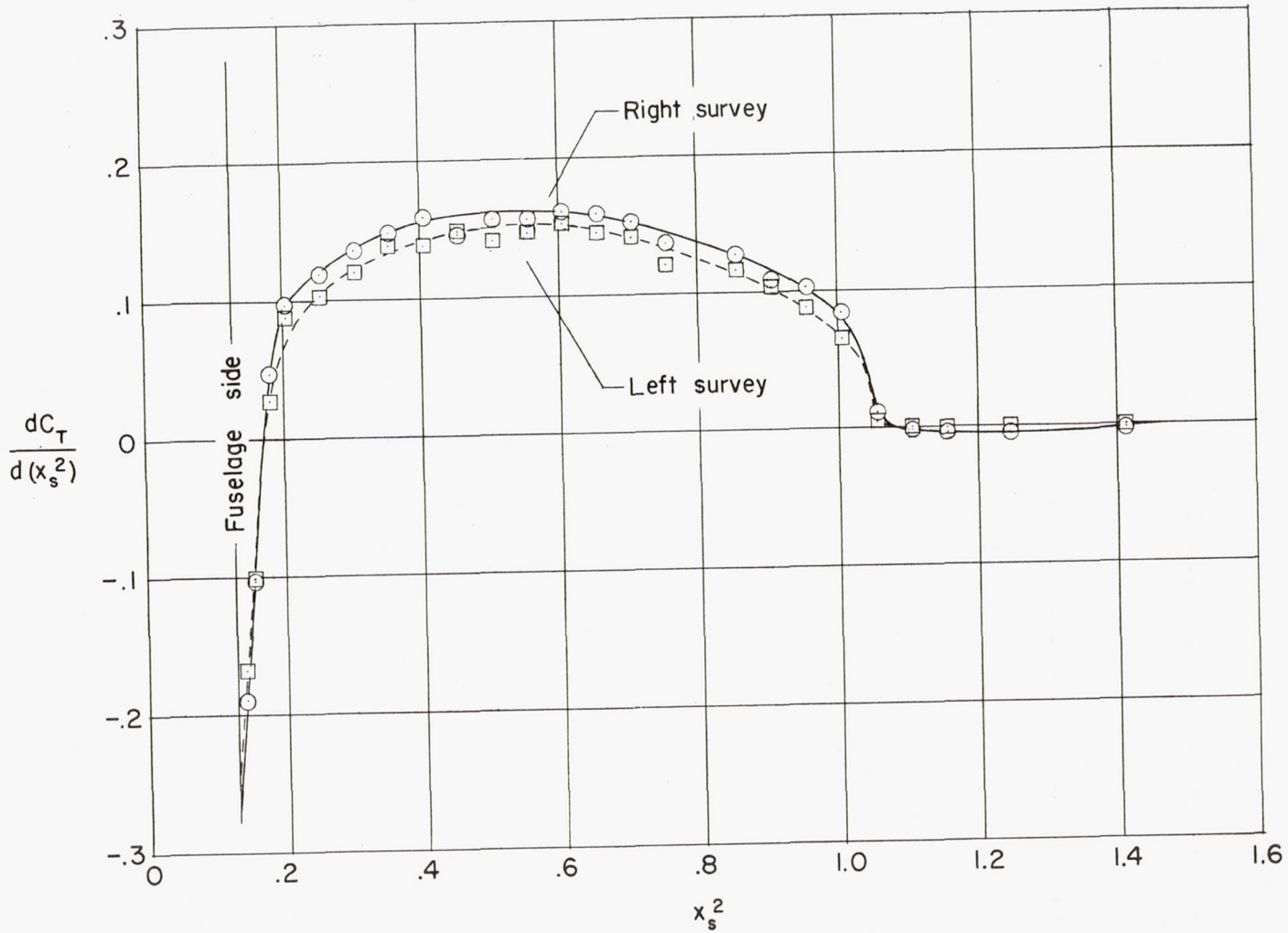
(b) $M_\infty = 0.799$; $J_\infty = 2.89$; $C_P = 0.396$; $M_t = 1.180$.

Figure 8.- Continued.



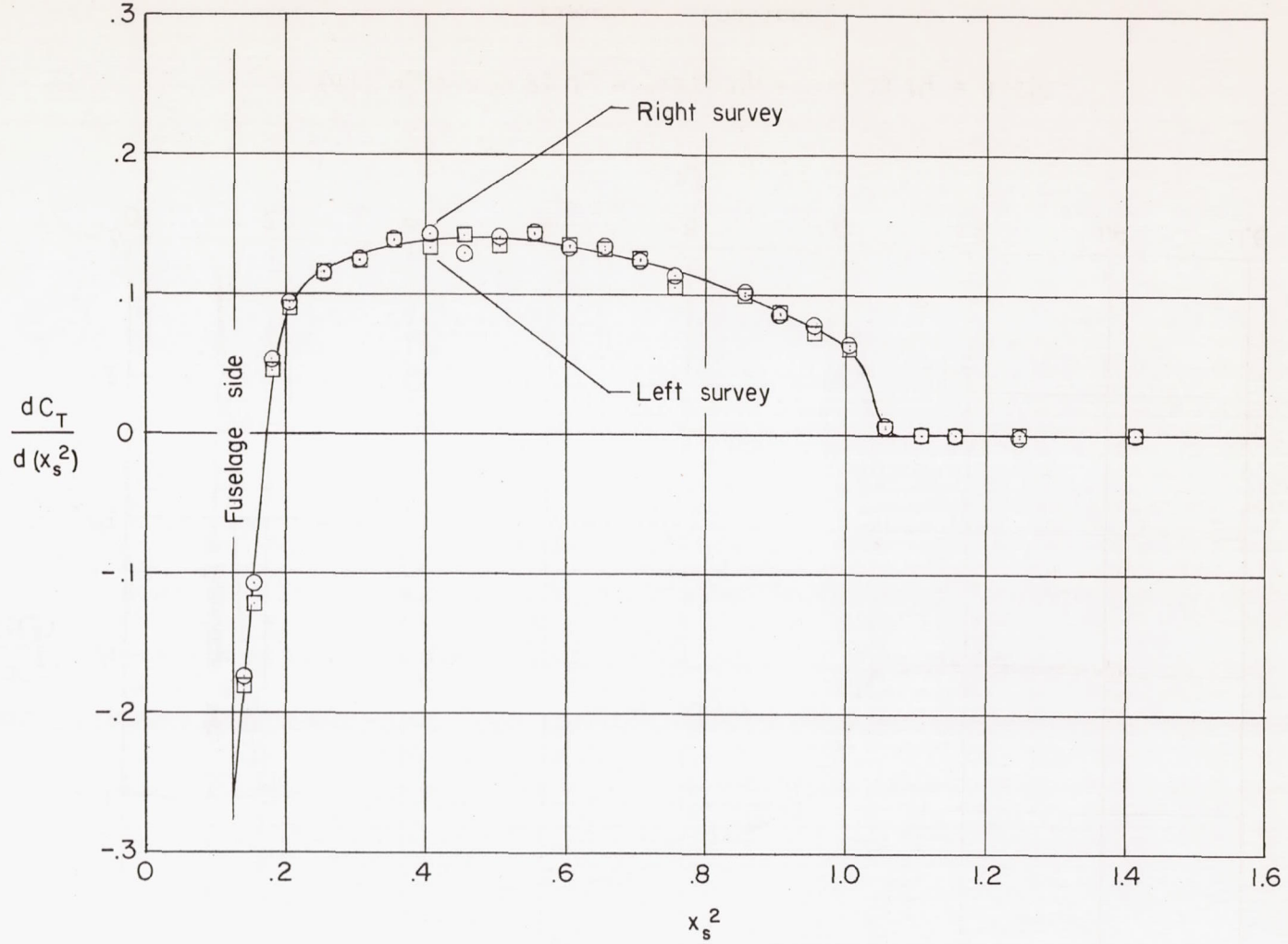
(c) $M_\infty = 0.852$; $J_\infty = 3.08$; $C_P = 0.394$; $M_t = 1.217$.

Figure 8.- Continued.



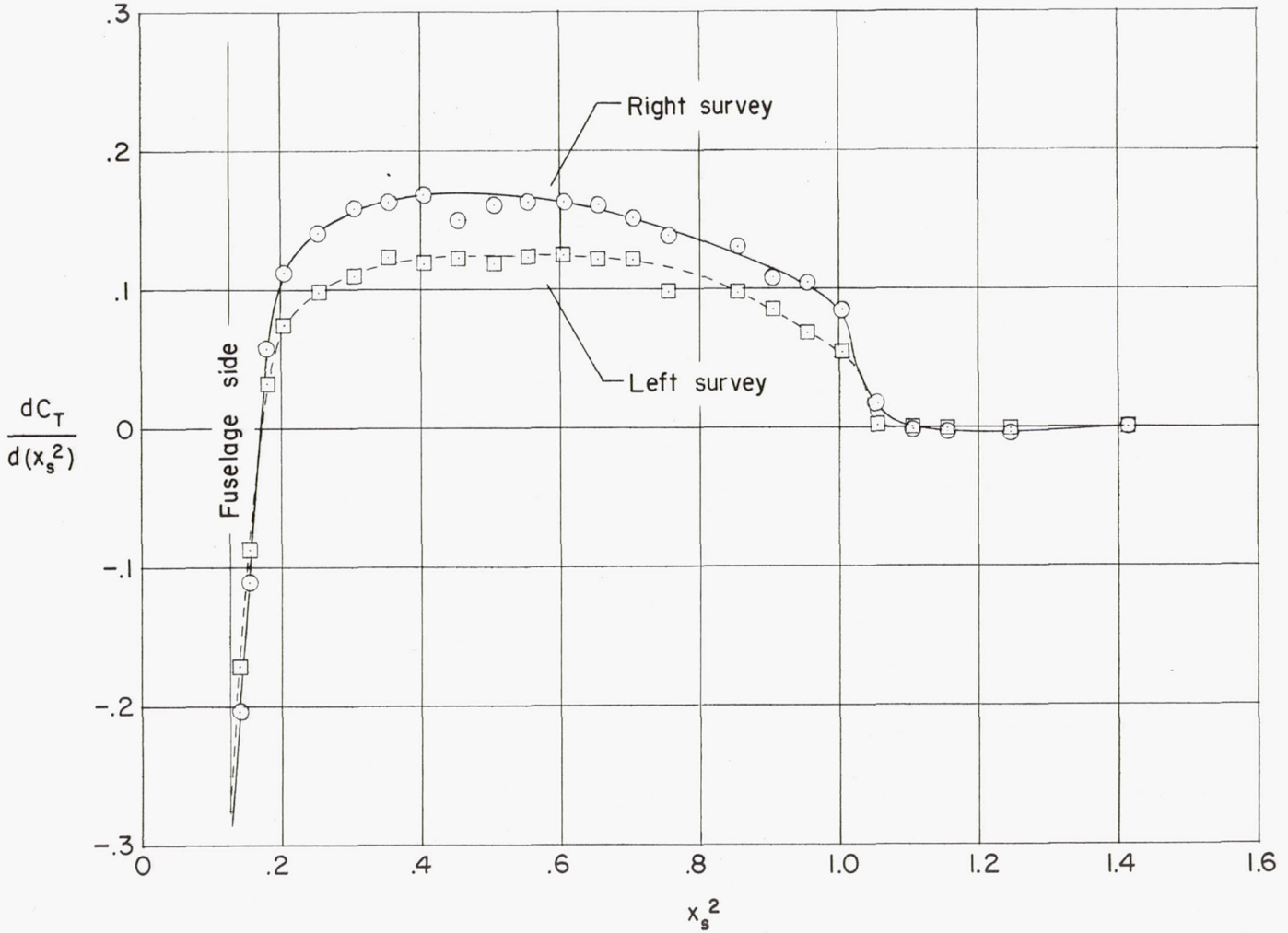
(d) $M_\infty = 0.902$; $J_\infty = 3.27$; $C_P = 0.411$; $M_t = 1.251$.

Figure 8.- Continued.



(e) $M_\infty = 0.926$; $J_\infty = 3.58$; $C_P = 0.415$; $M_t = 1.232$.

Figure 8.- Continued.



(f) $M_\infty = 0.948$; $J_\infty = 3.50$; $C_p = 0.413$; $M_t = 1.274$.

Figure 8.- Concluded.